

UNIT-3

CO1: To understand the basic concept of mode of heat transfer.

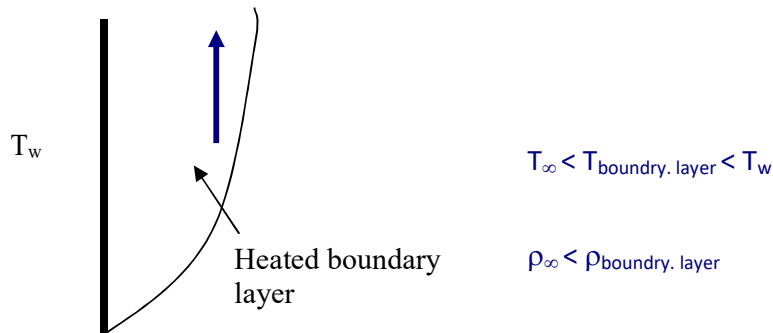
CO2: To apply non-dimensional numbers to evaluate and validate heat transfer parameters.

CO-3: To analyze the complex problems of heat transfer with proper boundary conditions.

SN	CONTENTS	HOURS
1	Natural convection: Dimensional analysis, Grashoff number, boundary layers in external flows (flow over a flat plate only), boundary layer equations and their solutions, heat transfer correlations.	4
2	Heat transfer with change of phase: Nature of vaporization phenomena; different regimes of boiling heat transfer; correlations for saturated liquid vaporization; condensation on flat plates; correlation of experimental results, drop wise condensation	4

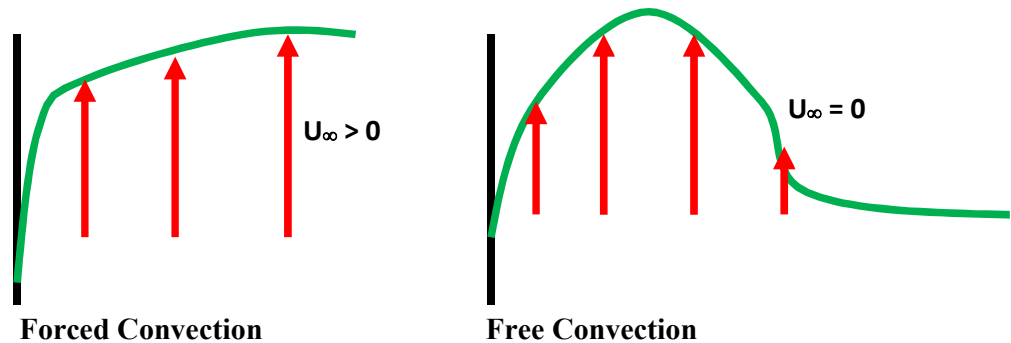
NATURAL CONVECTION

Natural (Free) convection is sometimes defined as a convective process in which fluid motion is caused by buoyancy effects.



Velocity Profiles

Compare the velocity profiles for forced and natural convection shown below:



Coefficient of Volumetric Expansion

The thermodynamic property which describes the change in density leading to buoyancy in the Coefficient of Volumetric Expansion, β .

$$\beta \equiv -\frac{1}{\rho} \cdot \left. \frac{\partial \rho}{\partial T} \right|_{p = \text{Const.}}$$

Evaluation of β

- Liquids and Solids: β is a thermodynamic property and should be found from Property Tables. Values of β are found for a number of engineering fluids in Tables given in Handbooks and Text Books.
- Ideal Gases: We may develop a general expression for β for an ideal gas from the ideal gas law:

$$P = \rho \cdot R \cdot T$$

Then,

$$\rho = P/R \cdot T$$

Differentiating while holding P constant:

$$\left. \frac{d\rho}{dT} \right|_{P=\text{Const.}} = - \frac{P}{R \cdot T^2} = - \frac{\rho \cdot R \cdot T}{R \cdot T^2}$$

P = Const.

Substitute into the definition of β

$$\beta = \frac{1}{T_{abs}}$$

Ideal Gas

Grashof Number

Because U_∞ is always zero, the Reynolds number, $[\rho \cdot U_\infty \cdot D]/\mu$, is also zero and is no longer suitable to describe the flow in the system. Instead, we introduce a new parameter for natural convection, the Grashof Number. Here we will be most concerned with flow across a vertical surface, so that we use the vertical distance, z or L , as the characteristic length.

$$Gr \equiv \frac{g \cdot \beta \cdot \Delta T \cdot L^3}{\nu^2}$$

Free Convection Heat Transfer Correlations

The standard form for free, or natural, convection correlations will appear much like those for forced convection except that (1) the Reynolds number is replaced with a Grashof number and (2) the exponent on Prandtl number is not generally 1/3 (The von Karman boundary layer analysis from which we developed the 1/3 exponent was for forced convection flows):

$$Nu_x = C \cdot Gr_x^m \cdot Pr^n$$

Local Correlation

$$Nu_L = C \cdot Gr_L^m \cdot Pr^n$$

Average Correlation

Quite often experimentalists find that the exponent on the Grashof and Prandtl numbers are equal so that the general correlations may be written in the form:

$$\text{Nu}_x = C \cdot [\text{Gr}_x \cdot \text{Pr}]^m$$

Local Correlation

$$\text{Nu}_L = C \cdot [\text{Gr}_L \cdot \text{Pr}]^m$$

Average Correlation

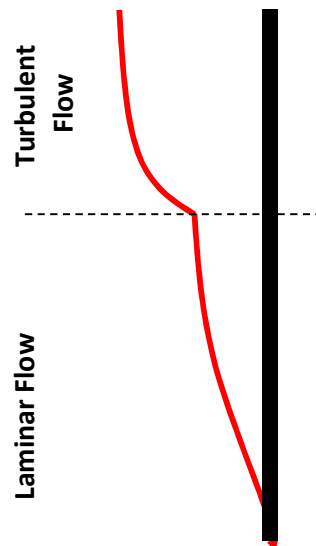
This leads to the introduction of the new, dimensionless parameter, the Rayleigh number, Ra:

$$\text{Ra}_x = \text{Gr}_x \cdot \text{Pr}$$

$$\text{Ra}_L = \text{Gr}_L \cdot \text{Pr}$$

Laminar to Turbulent Transition

Just as for forced convection, a boundary layer will form for free convection. The boundary layer, which acts as a thermal resistance, will be relatively thin toward the leading edge of the surface resulting in a relatively high convection coefficient. At a Rayleigh number of about 10^9 the flow over a flat plate will become transitional and finally become turbulent. The increased turbulence inside the boundary layer will enhance heat transfer leading to relative high convection coefficients because of better mixing.



$\text{Ra} < 10^9$ Laminar flow. [Vertical Flat Plate]

$\text{Ra} > 10^9$ Turbulent flow. [Vertical Flat Plate]

Vaporization phenomena

Vaporization (or vaporization) of an element or compound is a phase transition from the liquid phase to vapor. There are two types of vaporization: evaporation and boiling. Evaporation is a surface phenomenon, whereas boiling is a bulk phenomenon.

Evaporation is a phase transition from the liquid phase to vapour (a state of substance below critical temperature) that occurs at temperatures below the boiling temperature at a given pressure. Evaporation occurs *on the surface*. Evaporation only occurs when the partial pressure of vapour of a substance is less than the equilibrium vapor pressure. For example, due to constantly decreasing pressures, vapor pumped out of a solution will eventually leave behind a cryogenic liquid.

Boiling is also a phase transition from the liquid phase to gas phase, but boiling is the formation of vapor as bubbles of vapor *below the surface* of the liquid. Boiling occurs when the equilibrium vapor pressure of the substance is greater than or equal to the environmental pressure. The temperature at which boiling occurs is the boiling temperature, or boiling point. The boiling point varies with the pressure of the environment.

BOILING HEAT TRANSFER

It is used in various energy conversion and heat exchange systems and in cooling of high-energy-density electronic components. Pool boiling refers to boiling under natural convection conditions, whereas in forced flow boiling, liquid flow over the heater surface is imposed by external means.

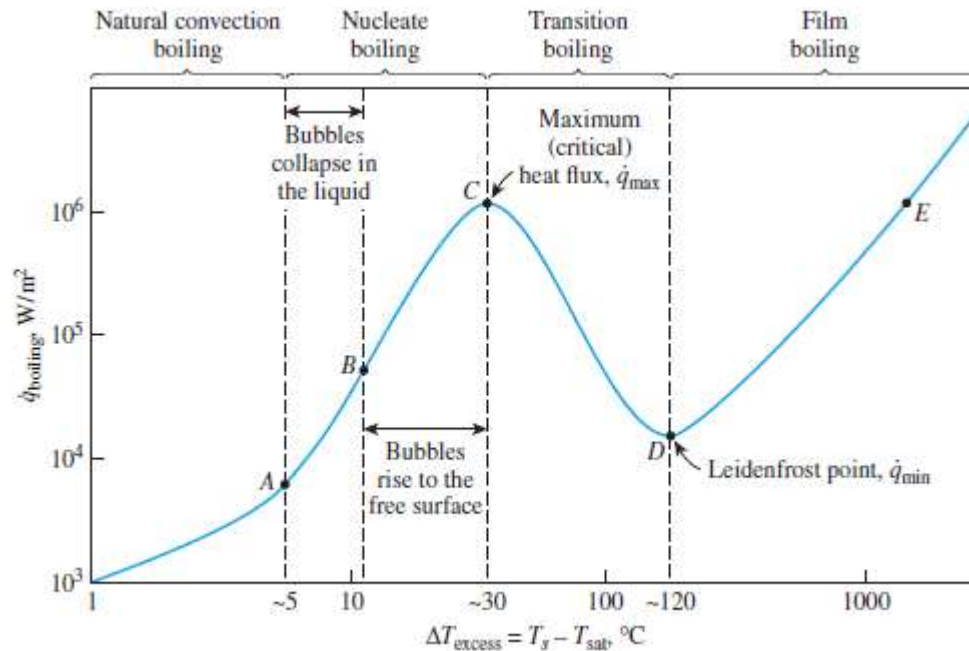
POOL BOILING:

So far we presented some general discussions on boiling. Now we turn our attention to the physical mechanisms involved in *pool boiling*, that is, the boiling of stationary fluids. In pool boiling, the fluid is not forced to flow by a mover such as a pump, and any motion of the fluid is due to natural convection currents and the motion of the bubbles under the influence of buoyancy.

As a familiar example of pool boiling, consider the boiling of tap water in a pan on top of a stove. The water is initially at about 15°C, far below the saturation temperature of 100°C at standard atmospheric pressure. At the early stages of boiling, you will not notice anything significant except some bubbles that stick to the surface of the pan. These bubbles are caused by the release of air molecules dissolved in liquid water and should not be confused with vapor bubbles. As the water temperature rises, you will notice chunks of liquid water rolling up and down as a result of natural convection currents, followed by the first vapor bubbles forming at the bottom surface of the pan. These bubbles get smaller as they detach from the surface and start rising, and eventually collapse in the cooler water above. This is subcooled boiling since the bulk of the liquid water has not reached saturation temperature yet. The intensity of bubble formation increases as the water temperature rises further, and you will notice waves of vapor bubbles coming from the bottom and rising to the top when the water temperature reaches the saturation temperature (100°C at standard atmospheric conditions). This full scale boiling is the *saturated boiling*.

Boiling Regimes and the Boiling Curve:

Boiling is probably the most familiar form of heat transfer, yet it remains to be the least understood form. After hundreds of papers written on the subject, we still do not fully understand the process of bubble formation and we must still rely on empirical or semi-empirical relations to predict the rate of boiling heat transfer.



1) Natural Convection Boiling (to Point A on the Boiling Curve)

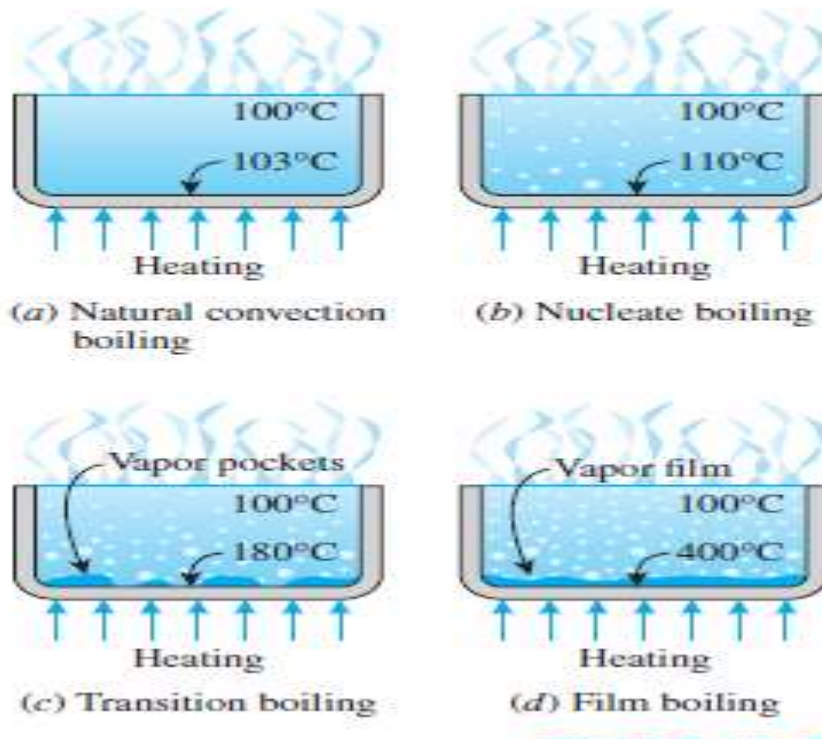
In thermodynamics that a pure substance at a specified pressure starts boiling when it reaches the saturation temperature at that pressure. But in practice we do not see any bubbles forming on the heating surface until the liquid is heated a few degrees above the saturation temperature (about 2 to 6°C for water).

2) Nucleate Boiling (between Points A and C)

The first bubbles start forming at point *A* of the boiling curve at various preferential sites on the heating surface. Point *A* is referred to as the *onset of nucleate boiling (ONB)*. The bubbles form at an increasing rate at an increasing number of nucleation sites as we move along the boiling curve toward point *C*. nucleate boiling exists in the range from about 5°C to about 30°C.

The nucleate boiling regime can be separated into two distinct regions. In region *A–B* (5°C to 10°C), *isolated bubbles* are formed at various preferential nucleation sites on the heated surface. But these bubbles are dissipated in the liquid shortly after they separate from the surface. The space vacated by the rising bubbles is filled by the liquid in the vicinity of the heater surface, and

the process is repeated. The stirring and agitation caused by the entrainment of the liquid to the heater surface is primarily responsible for the increased heat transfer coefficient and heat flux in this region of nucleate boiling.



In region $B-C$ ($10^\circ\text{C} \leq \Delta T_{\text{excess}} \leq 30^\circ\text{C}$), the heater temperature is further increased, and bubbles form at such great rates at such a large number of nucleation sites that they form numerous *continuous columns of vapor* in the liquid. These bubbles move all the way up to the free surface, where they break up and release their vapor content. The large heat fluxes obtainable in this region are caused by the combined effect of liquid entrainment and evaporation.

Transition Boiling (between Points C and D)

As the heater temperature and thus the ΔT_{excess} is increased past point C , the heat flux decreases, as shown in fig. This is because a large fraction of the heater surface is covered by a vapor film, which acts as an insulation due to the low thermal conductivity of the vapor relative to that of the liquid. In the transition boiling regime, both nucleate and film boiling partially occur. Nucleate boiling at point C is completely replaced by film boiling at point D . Operation in the transition boiling regime, which is also called the *unstable film boiling regime*, is avoided in practice. For water, transition boiling occurs over the excess temperature range from about 30°C to about 120°C .

Film Boiling (beyond Point D)

As the heater temperature and thus the ΔT_{excess} is increased past point C , the heat flux decreases. This is because a large fraction of the heater surface is covered by a vapor film, which acts as an insulation due to the low thermal conductivity of the vapor relative to that of the liquid. In the transition boiling regime, both nucleate and film boiling partially occur.

Nucleate boiling at point *C* is completely replaced by film boiling at point *D*. Operation in the transition boiling regime, which is also called the *unstable film boiling regime*, is avoided in practice. For water, transition boiling occurs over the excess temperature range from about 30°C to about 120°C.

Condensation:

Condensation occurs when the temperature of a vapor is reduced below its saturation temperature. Only condensation on solid surfaces is considered.

Two forms of condensation: –

- i) Film condensation
- ii) Drop wise condensation

Film condensation	Drop wise condensation
i) The condensate wets the surface and forms a liquid film	i) The condensed vapor forms droplets on the surface.
ii) The surface is blanketed by a liquid film which serves as a resistance to heat transfer.	ii) The droplets slide down when they reach a certain size. No liquid film to resist heat transfer
iii) 